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# Single- and multi-stage dairy wastewater treatment by vibratory membrane separation processes

Szabolcs Kertész*[1], Szabolcs Gyula Szerencsés[1a], Gábor Veréb[1b], József Csanádi[2b], Zsuzsanna László[1c] and Cecilia Hodúr[3c]

*[1]Department of Process Engineering, Faculty of Engineering, University of Szeged, H-6725 Szeged, Moszkvai krt. 9., Hungary*
*[2]Department of Food Engineering, Faculty of Engineering, University of Szeged, H-6725 Szeged, Moszkvai krt. 9., Hungary*
*[3]Institute of Environmental Science and Technology, University of Szeged, H-6725, Tisza Lajos krt. 103, Szeged, Hungary*

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**Abstract.** Before discharge into sewage or living waters, dairy effluents need to be effectively treated to meet the requirements defined by environmental protection regulations. In addition to the commonly used technologies, membrane separation might offer a novel solution with many remarkable advantages. Although membrane fouling often limits its industrial scale application, module vibration can reduce membrane fouling. In this study, multi-stage membrane separations with ultrafiltration (UF), as pre-filtration, and nanofiltration (NF) were investigated. On the one hand, our aim was to separate the wastewater to reach the cleanest permeate possible, on the other hand to achieve the highest organic content in the smallest volume for further energetic utilization. Firstly, with one-stage separations the effects of Vibratory Shear Enhanced Processing (VSEP) on shear rate, fluxes and rejections were investigated. These tests revealed that vibration has a positive effect on fluxes and rejections. Secondly, two types of multi-stage UF/NF separation experiments were carried out and membrane fluxes, COD rejections and flux decreasing rates were examined. In type 1, permeates of nanofiltered UF permeates achieved the lowest organic load in purified wastewater to meet European environmental threshold limits for living waters. In type 2, concentrates of nanofiltered UF concentrates reached the highest possible volume reduction ratio (VRR) resulting in higher organic content in a smaller volume, which could increase the efficiency of biogas production as an alternative post-treatment for waste management.

**Keywords:** ultrafiltration; nanofiltration; *VSEP*; shear rate; multi-stage; dairy wastewater; biogas

## 1. Introduction

As population growth rate and economic expansion increase, the pollution of our waters is of ever greater concern (Thines *et al.* 2017, Danner *et al.* 2019). Drinking water quality standards are threatened by industrial effluents, such as wastewater produced by the food industry. Production technology of the dairy industry has high water usage throughout the different steps, including the washing of equipment, containers and floor, sanitization, heating and cooling, as well as generating white water, effluents. Dairy effluents usually have high nitrogen, phosphorus, fat, protein and saccharide ratios, containing traces of milk and milk derivatives, and chemicals such as detergents used for cleaning (Karadag *et al.* 2015, Prince *et al*. 2018). Due to this, wastewaters can be characterized by high chemical oxygen demand (*COD*) and high biochemical oxygen demand (*BOD*), which could be converted into several valuable bioproducts, such as biofuels, feed additives, bioplastics or biogas (Chandra *et al.* 2018, Leh-Togi Zobeashia *et al.* 2018). These attributes can lead to serious environmental damage, such as eutrophication, unless proper wastewater treatment is applied before the effluents are discharged into sewage and especially into living waters (Badvipour *et al.* 2016). Therefore, the European Union continuously addresses these environmental issues – mainly by increasing protection regulations, in order to prevent damage to our waters. There are numerous methods available to meet the requirements of these regulations, such as biological or chemical oxidation, trickling filters and anaerobic sludge blanket (*UASB*) reactors, ion-exchange techniques, anaerobic filters, activated sludge processing or adsorption. Compared to these methods membrane separation is advantageous as it is easily combinable with other technologies and it uses very few chemicals, while it runs on mild operating parameters (Hyun *et al.* 2020, Frappart *et al.* 2008). Ultrafiltration can be a promising method to decrease the organic load of dairy effluents to meet the requirements of discharging into sewers while maintaining high fluxes at a relatively low transmembrane pressure (*TMP*) (Khosroyar and Arastehnodeh 2018). Nanofiltration (*NF*) offers higher

*Corresponding author, Associate Professor
E-mail: kertesz@mk.u-szeged.hu
[a] Student
E-mail: szabi1456@gmail.com
[b] Ph.D., Associate Professor
E-mail: verebg@mk.u-szeged.hu, csanadi@mk.u-szeged.hu
[c] Professor
E-mail: hodur@mk.u-szeged.hu, zsizsu@mk.u-szeged.hu


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Table 1 Model dairy wastewater characteristics at 50°C

| Turbidity | *COD* | Conductivity | Protein | Viscosity | Density | pH |
|---|---|---|---|---|---|---|
| [NTU] | [mg dm$^{-3}$] | [mS cm$^{-1}$] | [g g$^{-1}$] | [m Pas] | [kg m$^{-3}$] | [-] |
| 221.5 | 4770 ± 156 | 0.821± 0.03 | 0.35 ± 0.015 | 0.37 ± 0.017 | 983.9 ± 48 | 7.32 ± 0.34 |

organic load rejection, but requires higher *TMP* to maintain high fluxes. Unfortunately, membrane fouling still limits the application of membrane processes due to heavy flux decline and decreased membrane lifetime (Wang *et al.* 2020; Bian *et al.* 2000). Earlier results show that the use of vibratory shear enhanced processes (*VSEP*) can efficiently prevent fouling by producing a high shear rate on the surface of the membrane which can alter the cake layer (Akoum *et al.* 2005, 2006; Delaunay *et al.* 2008; Ding and Jaffrin 2014). Multiple researchers have concluded that multi-stage, integrated processes can be very effective for wastewater treatment (Andrade *et al.* 2014; Chen *et al.* 2017; Zhang *et al.* 2014). Luo et al have also measured higher fluxes and experienced less membrane fouling with the multi-stage *UF/NF* process than with the single *NF* method (Luo *et al.* 2011).

In the first part of this study, the feasibility of *VSEP* in dairy wastewater treatment was investigated by processing model dairy effluent with a laboratory mode *VSEP* equipped with different *UF* membranes and an *NF* membrane in order to know the fouling mitigation tendency. The impact of shear rates created by vibration on flux and rejection of *COD*, protein, lactose and salt values were analyzed and compared. Secondly, multi-stage *UF/NF* separation tests were carried out in order to know the possibility to reach the living water discharge thresholds. In this case different vibrational *UF* processes were tested as pre-treatment methods before non-vibrational *NF*. The *UF* permeates were filtered by *NF* as the second step of the treatment. Effects on the permeate flux, flux decreasing rates and rejection values were investigated. To investigate the biogas production tendencies, the *UF* concentrates were also concentrated with *NF*, to concentrate pollutants and organic matter into a smaller volume which is useful for post-treatments.

## 2. Materials and methods

### *2.1 Model dairy wastewater*

Model dairy wastewater (*ww.*) was prepared from skimmed milk powder (*ww.* concentration of 5 g dm$^{-3}$) (InstantPack, Hungary) and the anionic surfactant cleaning agent Chemipur *CL80* (*ww.* concentration of 0.5 g dm$^{-3}$) (Hungaro Chemicals, Hungary). Characteristics of the *ww.* at 50°C are given in Table 1. These characteristics are similar to real industrial dairy *ww*. (Burak *et al.* 2005).

### *2.2 Analytical methods*

The turbidity of the samples was determined with a Hach2100AN turbidimeter (Hach, Germany). The electric conductivity and pH were measured with a *BVBA* C5010 type multimeter (Consort, Belgium). The samples were tested using closed reflux method for *COD* analysis with an *ET* 108 digester and a *PC* CheckIt photometer (Lovibond, Germany). The lactose and dry content of the samples was measured by a Bentley 150 Infrared milk analyser (Bentley Instruments, USA). The protein and nitrogen contents of the samples were determined by the Kjeldahl method (Foss, Denmark). The viscosity and density of the samples were measured using a vibration viscometer (AND SV-10, Japan) and a portable density meter (Mettler-Toledo Densito 30PX, Switzerland). All of the analytical measurements were repeated three times to calculate an accurate average.

#### *2.2.1 Membrane filtration*

Single-step filtrations, the *UF* and *NF* experiments, were carried out using a *VSEP L/P* Series membrane device equipped with a single circular membrane of 0.0503 m$^2$ (New Logic Research Inc., USA). Supporting the membrane housing there is a vertical shaft, which acts as a torsion spring and transmits the oscillations of a lower plate, the base which is vibrated by an eccentric drive motor. As a result, the housing containing the membrane oscillates azimuthally with a displacement amplitude adjusted to 2.54 cm on the outer rim at the resonant frequency of 54.1 Hz. The detailed schematic diagram of the *VSEP* system with the calculated shear rates and transmembrane pressure and temperature stepping experiments can be found in our earlier paper (Kertész *et al.* 2017). Separation tests with *VSEP* were carried out at 50±1°C, *TMP* was set to 0.8 MPa for *UF*, and 3 MPa for *NF*. 10 L of feed model wastewater was ultra- or nanofiltered to a retentate volume of 2 L (to volume reduction ratio, *VRR* = 5). Recirculation flow rate was set to 4 *GPM* in every case.

In the multi-stage filtrations, due to the limited recirculation volume of the *VSEP* apparatus, only the *UF* pre-filtration could have been carried out, but for the second-stage another *NF* module had to be used. *NF* was done with a non-vibrational, Uwatech *3DTA* laboratory cross-flow membrane module (Uwatech Gmbh., Germany), with the use of flat-sheet 200 Da membranes (in Table 2) with a filtering surface area of 0.0156 m² and 2 MPa *TMP*. In this part, our aim was to reach the highest possible *VRR*, and a smaller volume is more efficient for this purpose. Compared to the 2 L dead volume of *VSEP*, the Uwatech *3DTA* has a significantly smaller, 0.2 L dead volume. 1.6 L of concentrate from the *UF* was used for concentration and processed to a retentate volume of 0.2 L (*VRR*=8). The *VRR* of *UF* was 5 and of *NF* was 8, so the two-stage concentrations resulted in a total *VRR* of 40.

#### *2.2.2 Membranes*

The *UF* and *NF* membranes were ordered from *VSEP* Company, but the producers were different (New Logic Research Inc., USA).

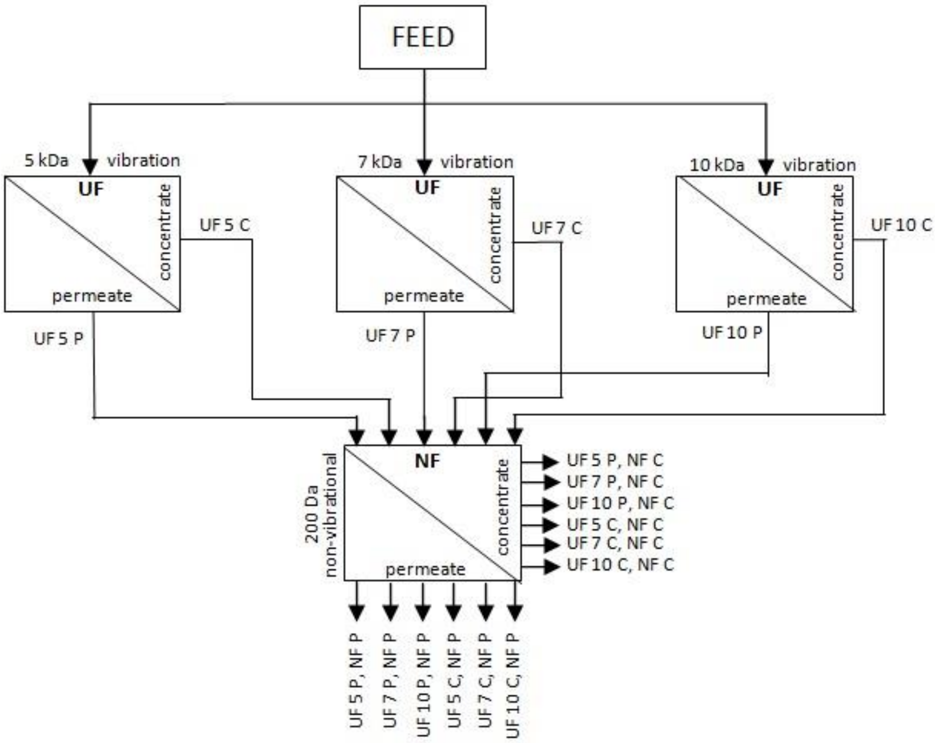



Fig. 1 Multi-stage experiment configuration

Table 2 Characteristics of the membranes used for our experiments

| Name | *PES-10 SYN* | *PES-5 TYVEK* | *PES-5 SYN* | *NF-3* | *SR3* |
|---|---|---|---|---|---|
| Filtration | *UF* | *UF* | *UF* | *NF* | *NF* |
| Material | Polyethersulfone | Polyethersulfone | Polyethersulfone | Thin film composite | Thin film composite |
| *MWCO* | 10000 Da | 7000 Da | 5000 Da | 240 Da | 200 Da |
| Vendor | Synder | Ultura | Synder | Sepro | Sepro |

### *2.2.3 Anaerobic biogas production tests*

Batch mesophilic anaerobic digestion tests were carried out at 37°C for 30 days to determine the biogas yield from the concentrates. Biogas production was detected by the pressure increase method in continuously stirred reactors with volumes of 250 mL equipped by OxiTop-C® measuring heads (WTW, Germany). The temperature was continuously controlled. The pH of the sample was adjusted to 7.2 in the beginning of the experiments. Sludge at 10 g $l^{-1}$ concentration was used as adaptation inoculum from the local mesophilic biogas digestor communal wastewater treatment plant.

### *2.2.4 Calculated parameters*

The selectivity of the membrane, *R* [%], for a given solute was expressed by the average retention (Eq. (1)):

$$R = \left(1 - \frac{c}{c_0}\right) 100 \quad (1)$$

where *c* is the average concentration of the solute in the permeate phase, and $c_0$ is the concentration of the solute in the feed *ww.*. The volume reduction ratio, *VRR* [-], was defined as

$$VRR = \frac{V_F}{V_F - V_p} \quad (2)$$

where $V_F$ is the volume of the feed [$m^3$] and $V_P$ is the volume of the permeate [$m^3$] at any time. The flux decreasing rate (*FDR*) [%] was expressed by the following eq.:

$$FDR = \left(1 - \frac{J_{WA}}{J_{WB}}\right) 100 \quad (3)$$

where $J_{WA}$ is the water flux of the fouled membrane after the experiment, and $J_{WB}$ is the water flux of the clean membrane before the experiment [$m^3$ $m^{-2}$ $s^{-1}$].

## 3. Results and discussion

### *3.1 Single-step experiments*

Single-step separation tests using *VSEP* were carried out to investigate the effects of vibration on fluxes and

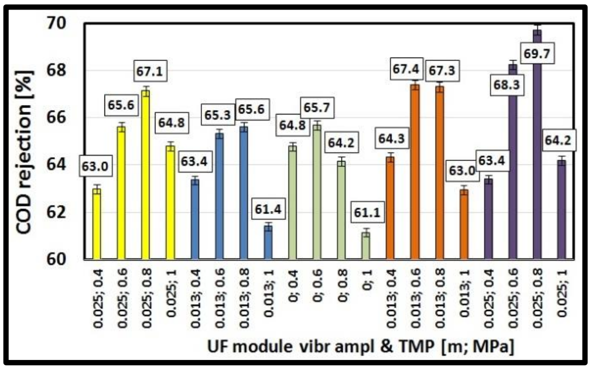



Fig. 2 The effect of vibration on COD rejections (*VSEP UF*: *PES* 10 kDa; $q_{vr}$ = 4 GPM)

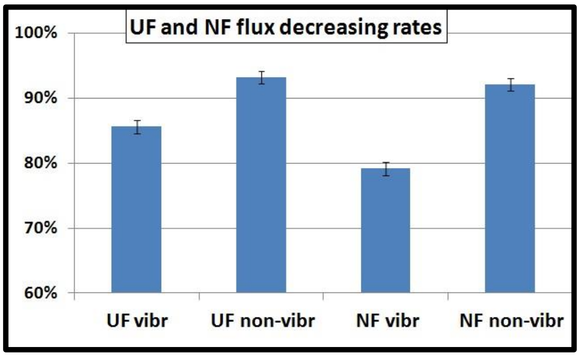



Fig. 3 The effect of vibration on flux decreasing rates (*VSEP UF*: *PES* 10 kDa; *VSEP NF*: *TFC* 240 Da, $q_{vr}$ = 4 GPM; VRR=5 for UF and 8 for NF)

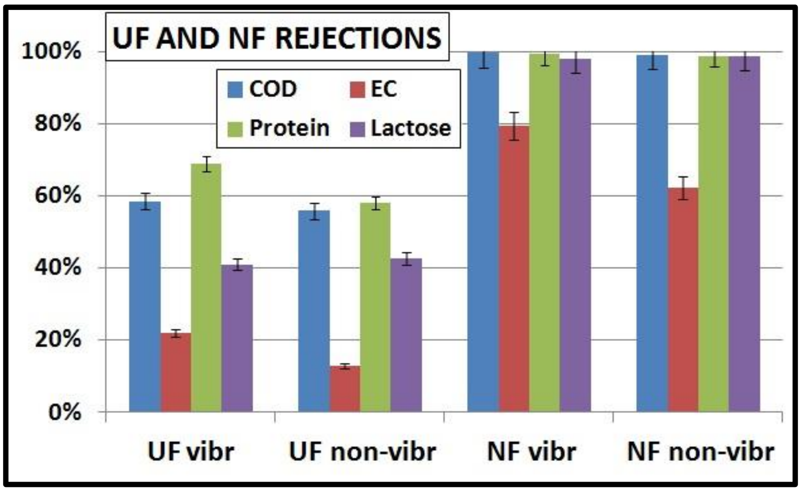



Fig. 4 The effect of vibration on *COD* rejections (*VSEP UF*: *PES* 10 kDa; *VSEP NF*: *TFC* 240 Da, $q_{vr}$ = 4 GPM)

rejections. The flux increasing effect of vibration in both *UF* and *NF* was remarkable and less time was needed to achieve the same 5 *VRR* by the end of each process.

The effects of different *TMP* (0.4; 0.6; 0.8 and 1 MPa) at various module vibration amplitudes (0; 0.013 and 0.025 m) on membrane *COD* rejection were studied during ultrafiltration and shown in Fig. 2. It was observed that in all cases *UF* membrane *COD* rejection increased from 0.4 to 0.8 MPa and then decreased suddenly. This was the main reason to use 0.8 MPa *TMP* for further multi-stage experiments in *UF* pre-filtration for the most efficient selectivity.

Flux decline is caused mainly by membrane fouling that can be inhibited by vibration, so calculating flux decreasing rates can be correlated to the effect of module vibration on membrane fouling. Fig. 3 shows that by vibration lessens the extent of membrane fouling in both *UF* and *NF*, which corresponds to the previously discussed effect of vibration increasing flux. In Fig. 4 it is visible that in both *UF* and *NF* chemical oxygen demand (*COD*), electric conductivity (*EC*), protein and lactose rejections could be increased by using vibration. *COD* rejection represents the total organic load rejection, and *EC* rejection shows the salts rejection. Because of its beneficial attributes in further multi-stage experiments vibrational *UF* is used (due to the limited recirculation volume of the *VSEP* apparatus, for the second-stage another *NF* module had to be used).

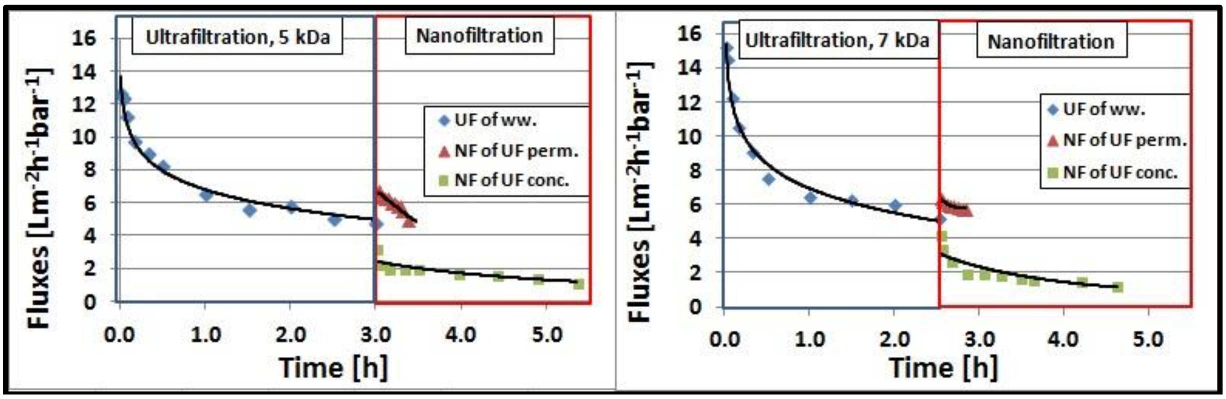
### *3.2 Multi-stage experiments*

To understand the effect of pre-filtration on the *NF* permeates and concentrates, shown in Fig. 5, multi-stage separations were tested with different *UF* pre-filtrations and with the same nanofiltration. Comparing the two different pre-filtrations, 7 kDa *UF* membrane had slightly higher initial fluxes, resulting in shorter filtration time than the 5 kDa *UF* for the same 5 *VRR*. It is noteworthy that the nanofiltrations of the different *UF* permeates practically took the same amount of time to reach the same 8 *VRR*. Regarding the nanofiltration of *UF* concentrates, the one with 7 kDa *UF* pre-filtration was slightly faster than the 5 kDa *UF* concentrate. We assume that the 7 kDa *UF* concentrate was more diluted compared to 5 kDa *UF*, because the higher *MWCO* results in more particles in the permeate, so the refiltration of the concentrate could not foul the membrane as much.

In Table 3, *COD* values of the concentrates and permeates from the multi-stage processes with the smallest *MWCO* membranes (5 and 7 kDa) are given, because these had the highest rejection percentages of the tested membranes. Comparing ultrafiltrations revealed that the 5 kDa *UF* pre-filtration yielded a permeate (*UF 5 P:* based on Fig. 1) with slightly lower *COD* and a concentrate (*UF 5 C*) with higher *COD*, but the difference is minor. After *NF*,

Table 3 Chemical oxygen demand (*COD*) and membrane rejection values in different process units

| 5 kDa Ultrafiltration (+ Nanofiltration) | | | 7 kDa Ultrafiltration (+ Nanofiltration) | | |
|---|---|---|---|---|---|
| Process Unit | COD [mg/L] | Rejection [%] | Process Unit | COD [mg/L] | Rejection [%] |
| Feed | 4770 ± 48 | - | Feed | 4770 ± 50 | - |
| UF 5 P | 1079 ± 11 | 77.38 ± 0.231 | UF 7 P | 1103 ± 12 | 76.88 ± 0.252 |
| UF 5 P, NF P | 55 ± 2 | 98.85 ± 0.042 | UF 7 P, NF P | 103 ± 4 | 97.84 ± 0.084 |
| UF 5 P, NF C | 4800 ± 46 | - | UF 7 P, NF C | 5180 ± 52 | - |
| UF 5 C | 10070 ± 101 | - | UF 7 C | 9657 ± 97 | - |
| UF 5 C, NF P | 342 ± 4 | 92.83 ± 0.084 | UF 7 C, NF P | 156 ± 3 | 96.73 ± 0.042 |
| UF 5 C, NF C | 25006 ± 250 | - | UF 7 C, NF C | 23640 ± 236 | - |




(a) (b)

Fig. 5 Normalized fluxes of multi-stage filtration test done with different pre-filtration membranes (*VSEP UF*: $A_{vibr}$ = 2.54 cm, 5 kDa/7 kDa *PES* membrane; Uwatech *NF*, 200 Da *TFC* membrane)

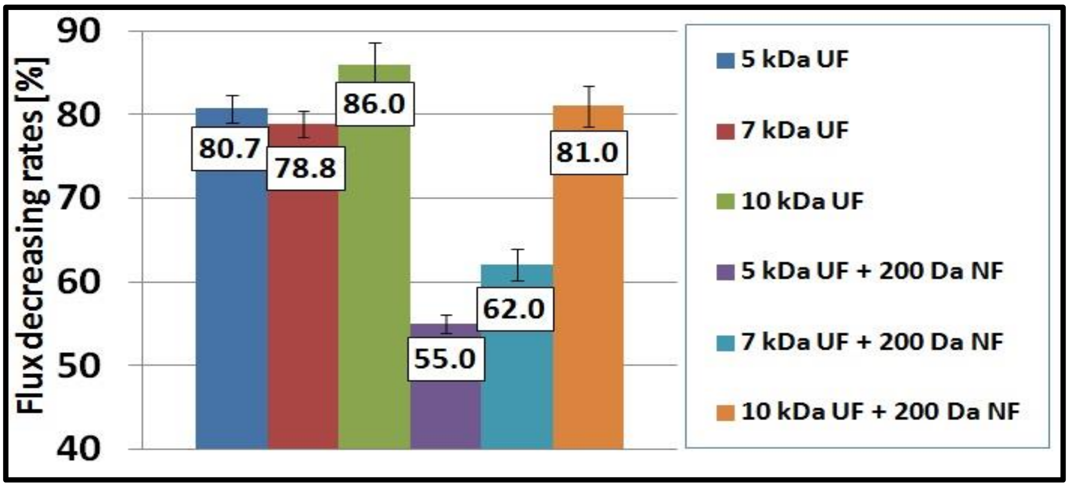



Fig. 6 Flux decreasing rates in *UF* and pre-filtered *NF* experiments (*VSEP UF*: $A_{vibr}$ = 2.54 cm, 5 kDa/7 kDa *PES* membrane; Uwatech *NF*, 200 Da *TFC* membrane)

permeate '*UF 5 P, NF P*' had a lower *COD* compared to the permeate '*UF 7 P, NF P*'. Although these values may seem quite small, the 103 mg $dm^{-1}$ value also meets the European living water discharge thresholds. It was also observed that, different concentration polarization structure and thickness were formed during the experiments in each case. Also, the *NF* of *UF* concentrates showed that the concentrate '*UF 5 C, NF C'* had higher *COD*, than concentrate '*UF 7 C, NF C'*, which indicates that the 5 kDa *UF* pre-filtration resulted in a more concentrated retentate, which can lead to more efficient post-treatments, such as biogas production, which will be discussed later in Fig. 7. Therefore we can conclude that whether our goal with the multi-stage process is to have a permeate with the lowest possible *COD* or to produce a concentrate with the highest possible *COD*, the 5 kDa *UF* filtration followed by *NF* is more efficient.

However, the whole multi-stage process (*UF*+*NF*) takes more time when pre-filtration is done with the 5 kDa membrane than with the 7 kDa membrane.

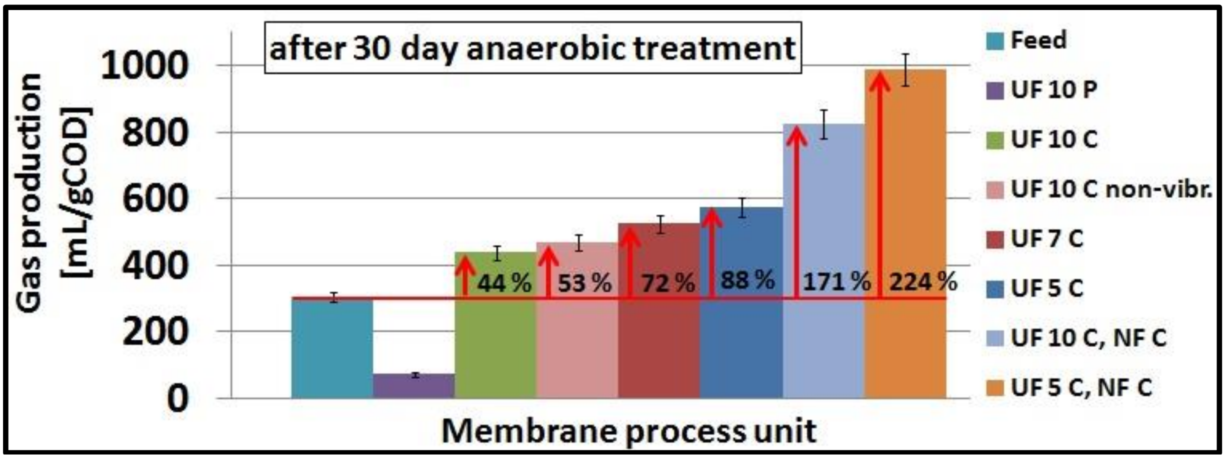



Fig. 7 Biogas production changes from UF and pre-filtered NF concentrates compared to original feed dairy wastewater (process units' names based on Fig. 1)

In Fig. 6, flux decreasing rates in the 5, 7 and 10 kDa *UF* and *UF* pre-filtrations followed by *NF* are compared. In all cases the 10 kDa *UF* has higher *FDR* than the 5 and 7 kDa *UF*, mainly because of its bigger pore size which results in more remarkable fouling. This Fig. also reveals that the *UF* process units alone have much higher *FDR* values than the combined *UF* + *NF* ones. Furthermore, the smaller *MWCO UF* membranes decreased the *FDR* of *NF*. Therefore we can conclude that *UF* pre-filtration, with a lower *MWCO* membrane, has a more beneficial effect on nanofiltration *FDR* values.

Biological pre-experiments were done in order to assess the amount of time needed to reach maximum biogas production for the tested feed dairy wastewater and it was observed that 30 days of anaerobic treatment is the optimal time. Therefore, Fig. 7 compares biogas production of the original dairy wastewater and samples from different process units after 30 days. The gas production changed depending on the treatment methods, since the membrane filtered wastewater composition could alter significantly. All of the *UF* concentrates had higher biogas production than the original feed, but the permeate of *UF* exhibited lower production. The volumetric biogas production (ml of produced biogas per organic content of the fermentation broth) changed according to the organic matter content of the concentrate. Fig. 7 shows that the concentrates of smaller *MWCO* membranes had higher biogas production. In terms of the effect of vibration, comparing '*UF 10 C*' to '*UF 10 C non-vibr.*', a slightly higher biogas production was observed in case of non-vibration. The nanofiltration process after *UF* increased biogas production, compared to original feed ww. by 171 and 224 % in the cases of '*UF 10 C, NF C'* and '*UF 10 C, NF C',* respectively.

## 3. Conclusions

In our study dairy wastewater purification was tested by both single- and multi-stage membrane separations. In single-stage experiments by applying vibration, membrane fouling can be reduced, thus, higher fluxes, less flux decline and slightly higher membrane rejections can be achieved in both ultrafiltration and nanofiltration.

In multi-stage type 1 experiments, the *UF* permeates were nanofiltered, as the *UF* was a pre-filtration process. The aim to meet European environmental *COD* threshold limits for living waters was successfully achieved. In multi-stage type 2 experiments, the *UF* concentrates were nanofiltered, the goal was to achieve the highest possible volume reduction ratio (*VRR*), with high organic content in a smaller volume, which could increase the efficiency of biogas production considerably. Nonetheless, a *VRR* of 40 was reached with certain concentrates, with the highest *COD* measured where the post-treatments are beneficial for biogas production. From biogas production experiments it can be concluded that all of the *UF* concentrates had higher biogas production than the original feed, but permeate of the *UF* produced less. The concentrates of smaller *MWCO* membranes had higher biogas production and nanofiltration after *UF* increased biogas production compared to the original feed ww. almost in average two times.

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## References

Akoum, O., Jaffrin, M.Y. and Ding, L.H. (2005), "Concentration of total milk proteins by high shear ultrafiltration in a vibrating membrane module", *J. Membr. Sci.*, **247**, 211–220. https://doi.org/10.1016/j.memsci.2004.09.021

Akoum, O., Richfield, D., Jaffrin, M.Y., Ding, L.H. and Swart, P. (2006), “Recovery of trypsin inhibitor and soy milk protein concentration by dynamic filtration”, *J. Membr. Sci.*, **279**, 291–300. https://doi.org/10.1016/j.memsci.2005.12.030

Andrade, L.H., Mendes, F.D.S., Espindola, J.C. and Amaral, M.C.S. (2014), “Nanofiltration as tertiary treatment for the reuse of dairy wastewater treated by membrane bioreactor”, *Sep. Purif. Tech.,* **126**, 21-29. https://doi.org/10.1016/j.seppur.2014.01.056

Badvipour, S., Eustance, E. and Sommerfeld, M.R. (2016), “Process evaluation of energy requirements for feed production using dairy wastewater for algal cultivation: Theoretical approach”, *Algal Res.*, **19**, 207–214. https://doi.org/10.1016/j.algal.2016.08.017

Bian, R., Yamamoto, K. and Watanabe, Y. (2000), “The effect of shear rate on controlling the concentration polarization and membrane fouling”, *Desalination,* **131**(1-3), 225-236. https://doi.org/10.1016/S0011-9164(00)90021-3

Burak, D., Orhan, Y. and Turgut, T.O. (2005), “Anaerobic treatment of dairy wastewaters: a review”, *Process Biochem.*, **40**(8), 2583-2595. https://doi.org/10.1016/j.procbio.2004.12.015

Chandra, R., Castillo-Zacarias, C., Delgado, P. and Parra-Saldívar, R. (2018), “Review: A biorefinery approach for dairy wastewater treatment and product recovery towards establishing a biorefinery complexity index”, *J. Clean. Prod.*, **183,** 1184–1196. https://doi.org/10.1016/j.jclepro.2018.02.124

Chen, Z., Luo, J., Wang, Y., Cao, W., Qi, B., Wan, Y. (2017), “A novel membrane-based integrated process for fractionation and reclamation of dairy wastewater”, *Chem. Eng. J.*, **313**, 1061-1070. https://doi.org/10.1016/j.cej.2016.10.134

Danner, M.C., Robertson, A., Behrends, V. and Reiss, J. (2019), “Review: Antibiotic pollution in surface fresh waters: Occurrence and effects”, *Sci. Total Environ.*, **664**, 793–804. https://doi.org/10.1016/j.scitotenv.2019.01.406

Delaunay, D., Rabiller-Baudry, M., Gozálvez-Zafrilla, J.M., Balannec, B., Frappart, M. and Paugam, L. (2008), “Mapping of protein fouling by FTIR-ATR as experimental tool to study membrane fouling and fluid velocity profile in various geometries and validation by CFD simulation”, *Chem. Eng. Process.*, **47**(7), 1106–1117. https://doi.org/10.1016/j.cep.2007.12.008

Ding, L. and Jaffrin, M.Y. (2014), “Benefits of High Shear Rate Dynamic Nanofiltration and Reverse Osmosis: A Review”, *Sep. Sci. Tech.,* **49**, 1953-1967. https://doi.org/10.1080/01496395.2014.914538

Frappart, M., Jaffrin, M. and Ding, L. H. (2008), “Reverse osmosis of diluted skim milk: Comparison of results obtained from vibratory and rotating disk modules”, *Sep. Purif. Tech.,* **60**(3), 321-329. https://doi.org/10.1016/j.seppur.2007.09.007

Hyun, U.C., Minjeong, L., Jingyeong, S., Eun-Sik, K. and Young, M.K. (2020), “Lignin fractionation from waste wood using organosolv treatment combined with membrane filtration”, *Membr. Water Treat.*, **11**, 25-29. https://doi.org/10.12989/mwt.2020.11.1.025

Karadag, D., Köroglu, O. E., Ozkaya, B. and Cakmakci, M. (2015), “A review on anaerobic biofilm reactors for the treatment of dairy industry wastewater”, *Process Biochem.*, **50**, 262–271. https://doi.org/10.1016/j.procbio.2014.11.005

Kertész, Sz., Bor, P., Hodúr, C., Csanádi, J., Veréb, G., Kovács, I., Keszthelyi-Szabó, G. and László, Zs. (2017), “Effects of shear rate on membrane filtration”, *Desalin. Water Treat.*, **69**, 43-49. doi:10.5004/dwt.2017.0645

Khosroyar, S. and Arastehnodeh, A. (2018), “Using response surface methodology and Box-Behnken design in the study of affecting factors on the dairy wastewater treatment by MEUF”, *Membr. Water Treat.*, **9(5)**, 335–342. https://doi.org/10.12989/mwt.2018.9.5.335

Leh-Togi Zobeashia, S.S., Aransiola, S.A., Ijah U.J.J. and Abioye O.P. (2018), “Anaerobic digestion and agricultural application of organic wastes”, *Adv. Environ. Res.*, **7**(2), 73–85. https://doi.org/10.12989/aer.2018.7.2.073

Luo, J., Ding, L., Qi, B., Jaffrin, M.Y. and Wan, Y. (2011), “A two-stage ultrafiltration and nanofiltration process for recycling dairy wastewater”, *Bioresour. Technol.*, **102**(16), 7437–7442. https://doi.org/10.1016/j.biortech.2011.05.012

Prince, A., Sanjai, J.P., Amy, P.S., Kate, M.S., Minseung, P. and Sungpyo, K. (2018), “The effect of organic matter on the removal of phosphorous through precipitation as struvite and calcium phosphate in synthetic dairy wastewater”, *Membr. Water Treat.*, **9**(3), 163–172. https://doi.org/10.12989/mwt.2018.9.3.163

Thines, R.K., Mubarak, N.M., Nizamuddin, S., Sahu, J.N., Abdullah, E.C. and Ganesan, P. (2017), “Application potential of carbon nanomaterials in water and wastewater treatment: A review”, *J. Taiwan Inst.Chem. Eng.*, **72**, 116–133. https://doi.org/10.1016/j.jtice.2017.01.018

Wang, J., Cahyadi, A., Wu, B., Pee, W., Fane, A.G. and Chew, J.W. (2020), “The roles of particles in enhancing membrane filtration: A review”, *J. Membr. Sci.*, **595**, 117570. https://doi.org/10.1016/j.memsci.2019.117570

Zhang, W., Xiao, P. and Wang, D. (2014), “Central treatment of different emulsion wastewaters by an integrated process of physicochemically enhanced ultrafiltration and anaerobic–aerobic biofilm reactor”, *Bioresour. Technol.,* **159**, 150–156. https://doi.org/10.1016/j.biortech.2014.02.067

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